Rural electrification: the potential and limitations of solar power

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Anna Margret Aevarsdottir[†], Nicholas Barton[‡] and Tessa Bold[§]

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Abstract

This paper provides experimental evidence on the adoption of solar power at the household level. In partnership with a local NGO we designed a randomized field experiment in which households in rural Tanzania were offered the chance to purchase solar powered lamps with solar panels. The lamps are offered on credit and provide a clean source of lighting and a small amount of power enough, for example, to charge a mobile phone. The paper centers around two questions 1) how does demand for a solar powered light source vary with price? 2) are there spill over effects in adoption of a renewable energy source?

Our results indicate a slightly concave demand curve where small subsidies may induces a high probability of purchase. We also document positive spillovers in take up of the technology. Future work will explore the impact of social learning and information spillovers on technology adoption of solar energy and the impact of solar energy on household and individual outcomes.

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[†]IIES, Stockholm University anna.aevarsdottir@iies.su.se

[‡]Goethe University barton@econ.uni-frankfurt.de

[§]IIES, Stockholm University tessa.bold@iies.su.se

1 Introduction

There is a general consensus that energy, in particular electricity, is a key input to economic development. A small literature has established a positive relationship between electricity access and a range of household and individual outcomes. These include increases in female employment [Dinkelman, 2011] and improvements in education [Khandker et al., 2013] and health [Barron and Torero, 2014]. The focus of this project is to provide the first experimental evidence on the adoption and impact of solar power at the household level. We will examine how price, liquidity constraints and information influence the decision to adopt a clean and renewable energy source such as solar power. This study is motivated by three main observations. First, nearly 1.3 billion individuals around the world lack access to electricity, of those, over 600 million reside in sub-Saharan Africa [IEA, 2013, IEA, 2014]. Second, based on current grid expansion plans and high population growth, it is estimated that 530 million people in, primarily rural, sub-Saharan Africa will remain without grid connection for the next 30 years [IEA, 2014]. Finally, due to this slow progress in expanding national grids solar power is being promoted by many as a decentralized and clean solution for rural areas that requires minimal infrastructure investments. Despite the apparent high potential, very little is known about the benefits and limitations of solar power at the household level.

2 Contributions and Related Literature

The policy relevance of this project is immediate given the prominence in policy circles of the debate on how best to expand energy supply in rural areas of developing countries. In addition to providing robust evidence to inform the policy debate the aim of this study is to contribute to to several different strands of literature.

First, this paper expands the literature on technology adoption [Dupas, 2014, Cohen et al., 2015, Conley and Udry, 2010]. This will be the first study to provide comprehensive experimental evidence on renewable energy sources for rural electrification and how willingness-to-pay for energy can be influenced in the context of Sub-Sarahan Africa. In particular we will examine the role of liquidity constraints, information and learning in the decision making process. A problem facing policy makers that are responsible for expanding electrical grids into rural areas of developing countries is that willingness-to-pay is generally quite low. There are many reasons why this may be the case. First, families may be financially constrained and not have the liquidity necessary to connect to the grid and pay for services. Second, households may not be fully aware of the benefits of having access to electricity and therefore underestimate the returns to being connected. Third, for the benefits of connectivity to be fully realized complementary investments may be necessary (e.g. purchase of appliances) which put further strain on household resources and liquidity and limit the returns. An objective of our paper will be to understand how access to a low energy sources such as solar powered lighting can help generate demand for energy, increase willingness-to-pay and facilitate grid expansion in the future.

Second, it relates to the literature on the impact of electricity on household and individual level outcomes. Our paper will be the first to provide experimental evidence on how access to a decentralized, clean and low capacity source of electricity influences outcomes such as educational attainment for children, labor market participation of parents and household expenditures in a low income country. A small literature has established a positive relationship between electricity access and a range of household and individual outcomes. These include increases in female employment [Dinkelman, 2011, Grogan and Sadanand, 2013] and improvements in education [Khandker et al., 2013, Khandker et al., 2012] and health [Barron and Torero, 2014]. All of these papers, however, focus on how grid connectivity influences outcomes and only one – from El Salvador [Barron and Torero, 2014], a considerably richer country than Tanzania – provides experimental evidence.

Finally, this paper relates to the literature on how social networks influence the adoption of a new technology [Conley and Udry, 2010, Alem et al., 2016]. In this paper we will explore how neighbours' experiences with the new technology influences the adoption decisions of households within 12 months from the initation of the intervention.

3 Overview of the Study

3.1 Setting and Program Description

In partnership with a NGO working on providing solar solutions in rural communities in East Africa, we have designed a randomized field experiment in which households in rural Tanzania were offered the chance to purchase solar powered lamps with solar panels. In our study the lamps were offered at different levels of subsidization at the household level. The lamps are fitted with a mobile phone charging point and with a daily charge the lamps have enough capacity to provide the household with light for several hours and a small amount of power - enough to, for example, charge a mobile phone.

It may seem that this is a rather limited intervention given that the solar panels and lamps offered in our study are only able to provide a clean source of lighting and a limited amount of power. However, it has been documented that even for rural households in sub-Saharan Africa with grid connections, electricity consumption is generally quite low, typically in the range 50 and 100kWh per person per year. To put these numbers in context, annual consumption of 50kWh per person for a five person household would for example power a mobile phone, two compact fluorescent light bulbs and a fan for approximately five hours a day [IEA, 2014]. These low levels of energy consumption despite grid connections lend support to the idea that decentralized energy solutions with minimal infrastructure investments can serve as a short run energy solution in rural areas where demand for energy and willingness-to-pay is low.

Our partner organization has been working with schools in rural Kenya since 2010 to provide solar power energy solutions to households in off-grid areas. Recently they have expanded their operations into the Northern part of Tanzania. The NGO operates based on the following protocol: first the NGO establishes a partnership with each school to facilitate the distribution of the lamps and collection of payments. The NGO then organizes a meeting with parents of children in the school to demonstrate how the lamps work and explain the price and payment structure of the lamps. The process of distributing the solar lamps and collecting payments from households is then managed jointly by the Parent Teacher Association in the school and a local agent from the NGO. The current NGO model in Tanzania provides the lamps at the recommended retail price of 80,000 TSh ($40). Households are offered the lamps on credit and can repay over a number of months. The payment structure is such that households make an initial payment amounting to roughly a fourth of the total price and then pay the remainder of the cost in instalments over a 3 month period. While repayment rates are not yet available for the Tanzanian operations of the NGO, figures from Kenya suggest quite high repayment rates with roughly 95% of lamps repaid in full.

4 Experimental Design

We designed our experiment with two main considerations in mind. The first the ability to estimate a demand curve for solar lamps. By offering the lamps to households at differing price levels, we are able gain a relatively crude impression of the demand curve for solar lamps by observing the purchase decision in a take-it-or-leave-it offer. The second consideration was the ability to estimate the causal impact of the solar lamps on household outcomes. Based on our design we can use the variation in demand for lamps at different prices to induce variation in lamp ownership. Lamp ownership can thus be instrumented with the randomly assigned subsidy to estimate the causal effect of the solar lamp.

4.1 Sample Selection

The evaluation sample consists of a random sample of households in the catchment area of 69 primary schools in the district of Magu in Tanzania. The selection of Magu district was based on the expansion plans of our partner organization and the timing of the project funding. Based on the program structure of our partner organization the sample selection required a two step selection where we first select schools to be part of the study and then select households connected to each selected school.

4.1.1 Selection of schools

The selection of schools was randomized based on a list of all schools in Magu district provided by the Ministry of Education and Vocational Training (MoEV) in Tanzania. From the list we randomly selected 69 schools to participate in our study. Of the 69 schools 60 were randomly selected to receive the subsidy treatment. The remaining 9 schools were eligible for the standard program offered by the NGO.

4.1.2 Selection of students and households

From each of the selected schools we collected student rosters. From the student rosters we randomly selected 30 students per school. All households of students selected for the study were sent a letter introducing the NGO and its operational model and informing them of the possibility of participating in our study and asking the student's parents to come to the school for a baseline interview. Some students were not present at the distribution of letters. In case a selected student was not present they were replaced by another randomly selected student.[1]

It is unlikely that student absence is purely random. We will therefore attempt to measure the extent of this selection effect by this using grade data from the school along with attendance data prior to the implementation of the program. In spite of possible sample selection of those present, we feel these are the households who would be likely to purchase lamps in the first place and as such are a representative sample of the households of interest to the study in the Mwanza region, given that household's children would have to attend school to purchase a lamp anyway.

4.2 Treatment Assignment

Our main treatment instrument was a subsidy for a solar lamp, inducing variation in take-up of purchasing solar lamps. In addition to this we also cross randomized and distributed a free children's book to half of the sample. In other words the

[1] In case the replacement student was also not present we continued with random replacement until a present student was selected

book randomization was stratified such that half the households for any given subsidy level received a book. We can then consider the complementary effect of owning a book to read on the reading skills of the children. This second treatment will be studied in a separate paper but is not relevant to the analysis presented in this paper.

4.2.1 Assignment of treatment at school level

The 69 schools selected to be part of our study were assigned to one of the three following treatment categories, each with different percentage subsidies available:

A High average subsidy: $S_1 = \{0, 50, 100\}$

B Low average subsidy: $S_2 = \{0, 25, 100\}$

C No subsidy (Control schools)

We randomly assign 30 schools to treatment arm A, with a high average subsidy, and 30 schools to treatment arm B, with low average subsidy. The remaining 9 schools are assigned to control arm C, without any subsidies.

4.2.2 Assignment of treatment at household level

The treatment assignment of households, their level of subsidy, is determined by a random draw from the set of subsidies S assigned to the school. This randomization took place via a public lottery with the respondents following the baseline interviews. Each respondent drew a card without replacement from the full set of 30 possible outcomes. The different treatment and comparison groups are outlined in Table 1 and Table 2. Based on their draw the respondents were presented with a voucher for their subsidy s_i. They could then redeem the voucher by purchasing a lamp from the NGO through the school. The voucher was valid for 2 weeks from the date of the draw. During the entire experiment, households were able to buy lamps from the NGO at the full unsubsidized price.

In all project schools the NGO followed their standard protocol in advertising the information meeting to all households in the school through the teachers and students. During the meeting there was a demonstration of how the lamps and solar panels work and parents were given information on the price and payment structure of the lamp. The introductory meeting was conducted at the school and led by a representative from the NGO.

4.3 Data Sources

The primary sources of data are a baseline survey conducted immediately before treatment assignment and lamp purchase data from our partner NGO. Additional sources of data include a brief school survey, administrative data from the schools and administrative data from our partner organization.

4.3.1 Baseline Survey

To measure the core outcome variables we conducted a household level survey at baseline before program implementation for all households in the sample. The baseline consisted of a detailed household survey administered at the school. In this survey we collected information on general household and individual characteristics. The questionnaire also included questions on fuel consumption and expenditures. The expenditure questions are intended to measure the household level savings due to reduced fuel expenditures following the repayment period. The lamps may also provide household members with new income generating opportunities. Anecdotal evidence from conversations with our partner organization suggests that some households have used the lamps to sell mobile charging time to other households in the area or to rear animals such as chickens. In addition, the lamps may allow home-run businesses to stay open later into the evenings. At baseline we also conducted testing of students in both control and treatment schools using a standardized reading test prepared and administered by the research team. This will allow us to convincingly compare education outcomes of students across schools. Throughout the program, we are collecting administrative data from the NGO on take-up and repayment of the lamps.

4.4 Other data sources

We collect administrative data from two sources: the study schools and from our partner organization. The data from the schools includes enrolment, grades and attendance data for all students in each school, including those in our sample. The data from our partner organization includes disaggregated take-up data (lamp purchase data) and repayment data.

5 Hypotheses and Estimation Methodology

In what follows we will discuss our main hypotheses and estimation methodology for this study.

5.1 Take-up and spillovers in take-up

The first set of questions and hypotheses will test to what extent variation in subsidy levels has an impact on take up of the solar lamps and whether there are spill-over effects in take up.

1. How does demand for a solar powered light source vary with price?

   A number of studies on technology adoption have documented that demand for new technologies can be extremely sensitive to price with take-up dropping substantially when provision of a new technology goes from a full subsidy to a very low but positive price. For example, a study in Kenya found that adoption of bednets to prevent malaria dropped by 60 percentage points when the subsidy was reduced from full subsidy to 90% subsidy [Cohen and Dupas, 2010]. Another study from Kenya reports a reduction in take-up of deworming medication from 75% to 19% when reducing subsidization by 20 percentage points through the introduction of small user fees [Kremer and Miguel, 2007]. These observations from previous studies motivate our hypotheses below.

Hypotheses:

(a) higher level of subsidy is likely to have (no) positive impact on take-up of solar lamps

We estimate this hypothesis using the following equation:

$$L_{i,t} = \alpha + \beta s_i + \epsilon_i \tag{1}$$

where $L_{i,t}$ is an indicator for whether the household purchased a lamp in the initial baseline experimental phase (t).

$H_a(H_0) : \beta > 0(\beta \leq 0)$

(b) It is likely that the demand curve is non-linear (linear) i.e. higher levels of subsidy squared is likely to have (no) impact on take-up of solar lamps

We estimate this hypothesis using the following equation:

$$L_{i,t} = 1 = \alpha + \beta_1 s_i + \beta_2 s_i^2 + \epsilon_i \tag{2}$$

$H_a(H_0) : \beta_2 \neq 0(\beta_2 = 0)$

2. Are there spill over effects in adoption of a renewable energy source?

There are several reasons why providing one time subsidies for a new technology might be desirable. For example, subsidies may allow households to be exposed to a new technology and learn about its benefits. In addition, in some cases subsidies may generate social learning and information spillovers through a household's network thus providing spillover effects of the subsidy on technology adoption. In her recent study considering the takeup of improved bednets in Kenya [Dupas, 2014] demonstrates substantial geographical spillover effects within the market for health products. We thus explore both geographic and household social network spillovers in the following hypotheses.

Hypotheses:

(a) subsidy treatment of neighbours has (no) positive impact on households take up of solar lamp

We estimate this hypothesis using the following equation:

$$L_{i,t} = \alpha + \beta s_i + \gamma TreatmentIntensity_i + \epsilon_i \tag{3}$$

$H_a(H_0) : \beta > 0(\beta \leq 0)$

where $TreatmentIntensity_i$ can be measured in several different ways including the share of high subsidies and average treatment intensity of connected households as follows:

- $ShareHigh_i = \frac{\sum_{j=1}^{n} d_{ij} \mathbb{1}(s_j = high)}{\sum_{j=1}^{n} d_{ij}}$
- $Intensity_i = \frac{\sum_{j=1}^{n} d_{ij} \cdot s_j}{\sum_{j=1}^{n} d_{ij}}$ where $s_j \in \{1, 0.5, 0.25, 0\}$ is the subsidy level of household j.

A high subsidy is defined as a subsidy of 100% or 50% and d_{ij} is an indicator for whether household i and j are connected. We will use two measures of household connectedness

- geographic proximity of households (measured using GPS coordinates)
- reported households connections for household questionnaire

3. Do own learning and experience influence adoption of a renewable and clean energy source?

As mentioned before, one time subsidies may be justified if they increase long-run adoption and willingness to pay for a new technology. Therefore in what follows we study whether a household's own willingness to pay for solar lamps increases over time.

Hypotheses:

(a) subsidy treatment at baseline has (no) positive impact on households take up of solar lamp at follow up
We estimate this hypothesis using the following equation:

$$L_{i,t+1} = \alpha + \beta s_{i,t} + \epsilon_i \tag{4}$$

$H_a(H_0) : \beta > 0 \ (\beta \leq 0)$

6 Results

The following results are based on survey data from the baseline and take up data from our partner organization.

6.1 Summary statistics

Table 3 reports summary statistics from the baseline survey administered to households in our study. Households are fairly large with an average of 8.5 members. The majority of households in our sample are engaged in agricultural activities, of those around 36% report cultivation for sale outside the household. Around a quarter of households report any male employment outside the household and about 17% any female employment. Annual household income is on average roughly 1 million Tanzanian shillings which corresponds to about $460. The electrification rate is low with only 6% of households being connected. Slightly more than half of households report owning some type of solar lamp at baseline while only 5% of households report owning a large solar lamp comparable in functionality and quality to the product our partner organization is providing.

6.2 Balance at baseline

Across our main treatment variable, the level of subsidy, the sample appears to be balanced. There are no significant differences in any of the baseline variables in a regression on the subsidy level and a squared term. These results can be seen in Table 4 and show that the sample appears to be balanced for both demographic and household variables such as household size, female employment, income, bank account ownership, kerosene expenditure, and prior solar lamp ownership.

6.3 Take-up and spillovers in take-up

To gain a broader understanding of the take-up for lamps at different prices, we show predicted values for the probability of deciding to purchase a lamp according to the price, written as a fraction of the full price. This demand curve, shown in Figure 1 is clearly downward sloping. The graph shows points at the mean purchase decision of the households with each level of subsidy. A linear demand curve is then fitted to these points. The size of the circle is representative of the number of households at that subsidy level. Those with a full subsidy, i.e. with a price of zero, purchase the lamp with a probability of almost one, while among those with no subsidy take up was roughly 2%. As would be expected, at the intermediate subsidy levels the probability of purchase is between these values at the extreme subsidy levels of zero and 100%. For those receiving a 50% subsidy, they buy the lamp with a probability of around 63%. For those with only a 25% subsidy, the purchase probability is around 39%. The predicted purchase probabilities from a take-it-or-leave-it offer are close to a linear demand curve, with the actual take-up values slightly above the line for the intermediate subsidy levels. The fact that they are above the line, may be suggestive of a concave demand curve where some subsidy induces a high probability of purchase.

Following the methods outlined in subsection 5.1, we first run a simple regression of the purchase decision on the subsidy level, which can be seen in column 1 of Table 5. The results show that there is a highly significantly positive effect of the subsidy on the decision to buy a lamp. This positive effect is analogous to the downward sloping demand curve just presented, simply with the subsidy level being the dependent variable rather than the price. By including a squared term in column 2, we test for the convexity of the demand curve. Not only is the squared term for subsidy not positive, it is significantly less than zero and so suggests a concave demand curve. In this case the fact that an individual has received a discount at all is important in the purchase decision, rather than requiring a high subsidy to purchase the lamp.

We now consider the possible impacts of spillovers in take up at the school level using data from our baseline. These estimate are presented in columns 5 and 6 of Table 5. The results indicate that there are positive spillover effects in take-up. The estimates in column 6 indicate that a 10 percentage point increase in the share of households with full subsidy in the school increases the probability that a household buys a lamp by 6.78 percentage points.

7 Conclusion

This paper presents evidence from a field experiment that studies the impact and adoption of solar power. The study is set in a rural district of Tanzania where household access to electricity is extremely low. The policy relevance of this project is immediate given the prominence in policy circles of the debate on how best to expand energy supply in rural areas of developing countries. In addition to providing robust evidence to inform the policy debate, the aim of this study is to contribute to to several different strands of literature.

To gain a broader understanding of the take-up for lamps at different prices, we show predicted values for the probability of deciding to purchase a lamp according to the price, written as a fraction of the full price. The predicted purchase probabilities from a take-it-or-leave-it offer are close to a linear demand curve, with the actual take-up values only slightly above the line for the intermediate subsidy levels. The fact that they are above the line, may be suggestive of a concave demand curve where some subsidy induces a high probability of purchase. Our results also indicate that there are positive spillover effects in take-up, a 10 percentage point increase in the share of households with full subsidy in the school increases the probability that a household buys a lamp by 6.78 percentage points.

Future work will study the impact of solar energy on household and individual outcomes such as education, employment, air quality and health. Our endline data set will also allow us to investigate spillovers in technology adoption more closely by using household network and geographic data. In addition, we will study learning about a technology by studying take up and spillovers in take up a year after the initation of the project.

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8 Appendix

Table 1: Sample size and treatment assignment

		Textbook (B)	No Textbook (NB)
Lamp subsidy:	100% (H & L)	300	300
	50% (H)	150	150
	25% (L)	150	150
	0% (H & L)	300	300
	0% (C)	-	300

Table 2: Treatment Arms

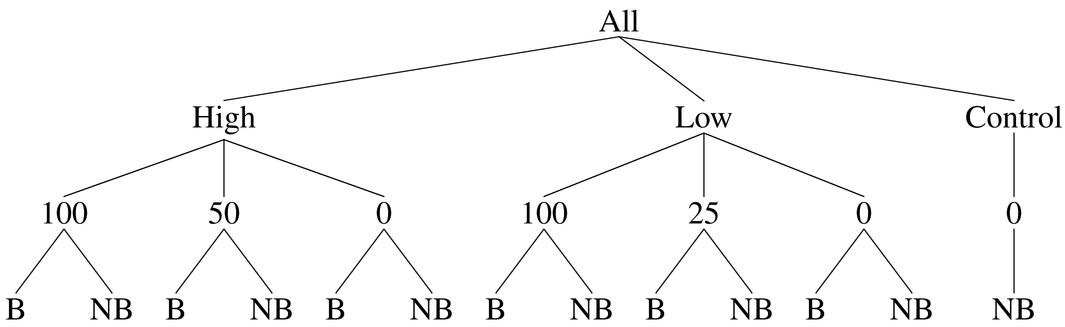

Figure 1: Demand curve

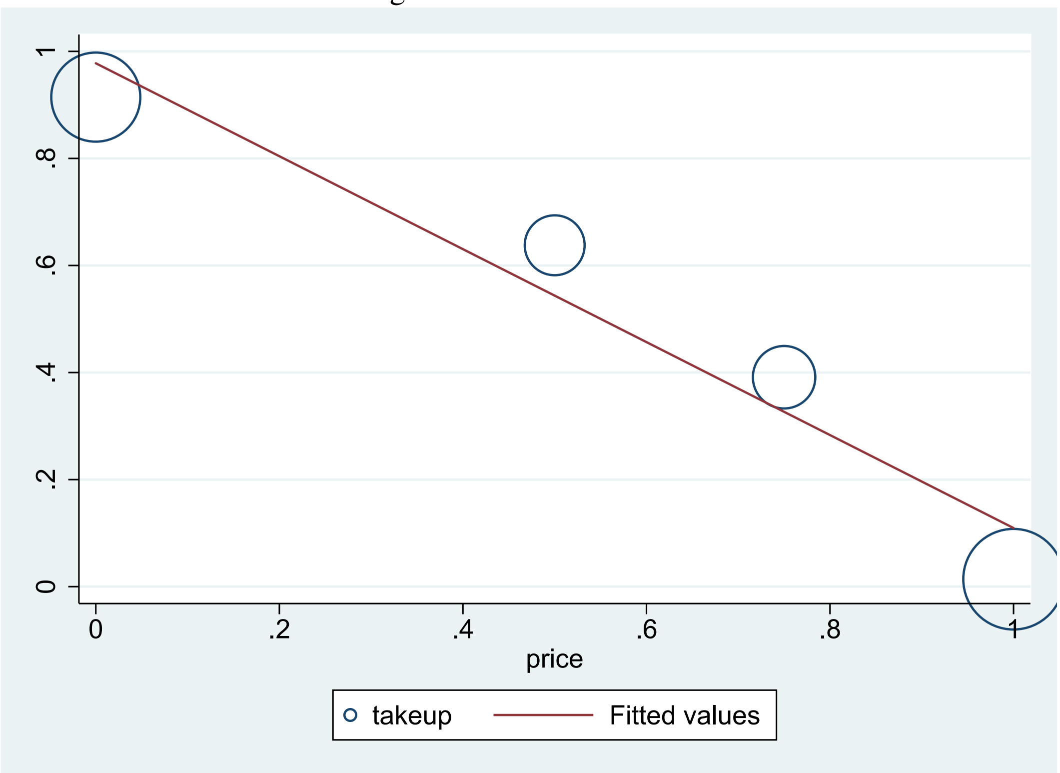

Table 3: Characteristics at baseline

	Full Sample
Household size	8.46
	(2.961)
Cultivation for consumption	0.88
	(0.321)
Cultivation for sale	0.36
	(0.480)
Any male employment outside hh	0.24
	(0.427)
Any female employed outside hh	0.17
	(0.373)
Household income	989.57
	(4138.5)
Household has bank account	0.10
	(0.294)
Expenditures on lighting in last week	752.55
	(1883.0)
Expenditures on kerosene in last week	454.43
	(954.3)
Household has electricity	0.06
	(0.232)
Any solar lamp	0.57
	(0.495)
One or more large solar lamp	0.05
	(0.223)
N	1830

Standard deviations in parentheses.
Household income in 1000 shillings

Table 4: Balance table - lamp subsidies

	(1) hh size	(2) female empl	(3) hh income	(4) account	(5) kerosene	(6) nonsolar
subsidy	0.06	0.00	145.98	0.08	300.24	0.05
	(0.75)	(0.09)	(106.86)	(0.07)	(241.00)	(0.13)
subsidy2	-0.30	-0.00	-155.32	-0.09	-283.14	-0.03
	(0.71)	(0.09)	(100.45)	(0.07)	(226.45)	(0.12)
Observations	1823	1829	1829	1823	1823	1829
F	2.39	3.29	1.38	3.26	2.69	2.04

Standard errors in parentheses
All regressions include school fixed effects
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Take up and Spillovers

	(1) Lamp	(2) Lamp	(3) Lamp	(4) Lamp	(5) Lamp	(6) Lamp
subsidy	0.864***	1.579***			0.846***	
	(0.0181)	(0.0778)			(0.0195)	
subsidy2		-0.709***				
		(0.0750)				
100%			0.674***			0.632***
			(0.0193)			(0.0196)
50% or more				0.682***		
				(0.0168)		
average subsidy in school					0.129**	
					(0.0522)	
share w. 100% subsidy in school						0.678***
						(0.0780)
Observations	1829	1829	1829	1829	1829	1829